Electronic characteristics of Ge and InGaAs radiometers

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ABSTRACT

Custom-made Ge and InGaAs photodiodes were tested for high sensitivity DC and AC radiometric applications. Equal size, large-area photodiodes were selected and used as optical sensors in NIST's near-infrared (NIR) standard radiometers. The DC electronic characteristics of the Ge and InGaAs radiometers were measured versus photodiode temperature. At -30 °C, a limit-sensitivity of 22 fA and a dark-current stability of 0.2 pA/16 hours was achieved with the InGaAs radiometer, which was three times better than the results obtained with the Ge radiometer. The Ge radiometer was used for DC signal measurements only, because at frequencies higher than 0.3 Hz the noise boosting effect decreased the photocurrent sensitivity. The frequency dependent gain characteristics were calculated and compared for the two types of radiometer. The InGaAs radiometer could measure optical radiation with a chopping frequency of 10 Hz without any response or limit-sensitivity degradation.

Keywords: dynamic range, frequency dependence, near infrared, noise, photocurrent, photodiode, radiometry, sensors, standard, temperature dependence

1. INTRODUCTION

Germanium (Ge) and Indium-Gallium-Arsenide (InGaAs) radiometers were designed and fabricated at NIST[1] to measure NIR radiometric quantities with high accuracy over a wide range of signal levels. Large-area, planar-structure InGaAs photodiodes with dielectric passivation were selected for most of the applications. For comparison purposes, large-area Ge photodiodes, with diffused, shallow n-type junction over the p-type base material, were built and tested as well.

Large photodiode surfaces of optical quality (polished) were necessary to make optical alignments simple and to eliminate radiation scatter. The diameter of the active area was 5 mm for both the InGaAs and the Ge photodiodes. The plane of the photodiode surface was 2° out of parallel with the wedged window to avoid interference during laser measurements. The photodiodes were selected for high shunt resistance to obtain low amplification of the voltage noise[2]. All photodiodes were hermetically sealed in standard housings of the same size and were cooled by two-stage thermoelectric coolers. The temperatures of the photodiodes were monitored by thermistors and controlled by temperature controllers[3].

2. LOW FREQUENCY (DC) CHARACTERISTICS OF THE NIR RADIOMETERS

The Ge and InGaAs photodiodes were temperature controlled between 25 °C and -30 °C in order to measure their temperature dependent characteristics. Short circuit current measuring circuits of low noise and low drift were attached to the photodiodes[2] to achieve linear operation over a wide radiant power range. The radiometer electronic characterizations included measurement of shunt resistance, voltage gain, output offset voltage, input noise, photocurrent sensitivity, and short term instabilities.

The shunt resistance of the selected Ge photodiode was 17 kΩ at 25 °C. This value increased to 20 MΩ at -30 °C. The three orders of magnitude shunt resistance change of the Ge photodiode had a large impact on the voltage gain[2] of the photocurrent-to-voltage (I-V) converter. The measured shunt resistance and the calculated DC voltage gain are shown versus temperature in Figure 1. The same measurements were repeated on the selected InGaAs photodiode radiometer. The shunt resistance and the DC voltage gain are shown versus the InGaAs photodiode temperature in Fig. 2. The changes with the InGaAs radiometer are about 40 times smaller as compared to the changes with the Ge radiometer.

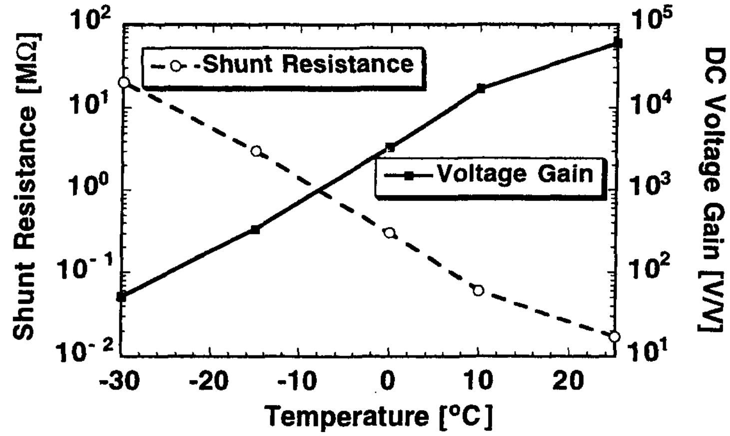

Figure 1. Temperature dependent shunt resistance and DC voltage gain of the Ge radiometer

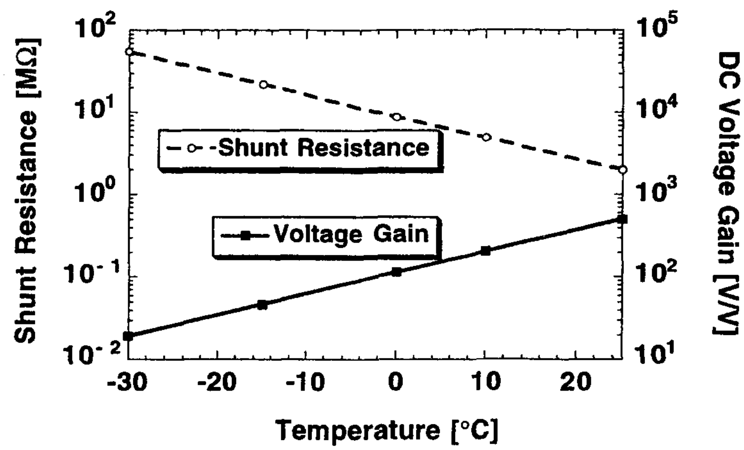

Figure 2. Temperature dependent shunt resistance and DC voltage gain of the InGaAs radiometer

The output offset voltages of the two radiometers were also measured versus temperature. The results are shown in Fig. 3. The output offset voltage of the Ge radiometer changed by more than 300 mV because of the large change in the voltage gain with temperature. The output offset voltage change with the InGaAs radiometer was only 6 mV. The maximum value was 290 mV with the Ge radiometer and 8.2 mV with the InGaAs radiometer. The estimated relative uncertainty (coverage factor k=1) of the offset voltage measurements was 5 % and that of the shunt resistance measurements was 10 %.

The input voltage noise characteristics were determined for both radiometers. The input voltage noise is the ratio of the measured output voltage noise to the voltage gain. The output voltage noise of the radiometer is equal to the standard deviation of the mean output offset voltage (when no optical radiation is measured by the photodiode). In Fig. 4, the measured input voltage noise characteristics are shown versus temperature for both radiometers. Both devices exhibit similar behavior. The same Model OPA111[4] operational amplifiers were used in both cases. The noise at low photodiode temperatures is higher than at room temperature. At low temperatures the shunt resistance noise of the photodiode is comparable to the $1/f$ voltage noise of the operational amplifier. This is also illustrated in Fig. 5. The total input voltage noise is the superposition of these two major noise components. The total noise measurements of Fig. 5 were made on the InGaAs radiometer at a current-to-voltage gain of 10^9 V/A. At this gain the resistor noise was dominated by the 55 MΩ shunt resistance of the InGaAs photodiode (at -30 °C). The $1/f$ voltage noise of the operational amplifier was flat for shunt resistances less than about 10 MΩ. The resistor noise was calculated using the 0.3 Hz electrical bandwidth of our measurements.

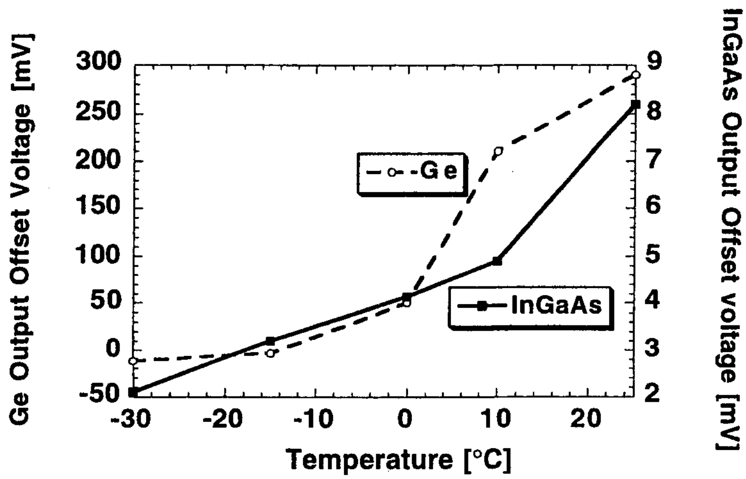

Figure 3. Temperature dependent output offset voltages of the Ge and InGaAs radiometers

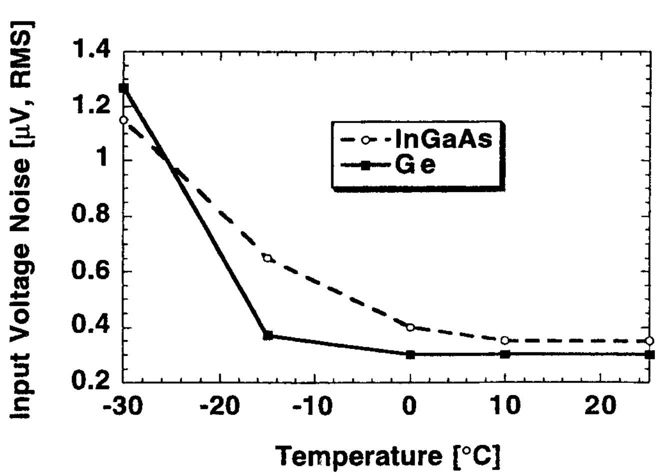

Figure 4. Temperature dependent input voltage noise of the Ge and InGaAs radiometers

The noise equivalent photocurrent is the ratio of the output voltage noise to the current-to-voltage gain (the feedback resistor of the I-V converter). The noise equivalent current gives the photocurrent sensitivity of the radiometer. Despite of the similar input noise characteristics of the Ge and InGaAs radiometers, the photocurrent sensitivities and their temperature dependences are different. This is shown in Fig. 6. The change of the photocurrent sensitivity with the InGaAs radiometer was less than a factor of 8, whereas that of the Ge radiometer was a factor of 290. To achieve high sensitivity and stability, temperature controlled cooling was required for the highly temperature dependent Ge photodiode. Temperature control was not necessary to get similar performance from the InGaAs photodiode. 22 fA noise equivalent photocurrent was measured at a bandwidth of 0.3 Hz with the InGaAs radiometer when the photodiode was cooled and controlled at -30 °C. The relative uncertainty (coverage factor k=1) of the noise measurements was 26 %.

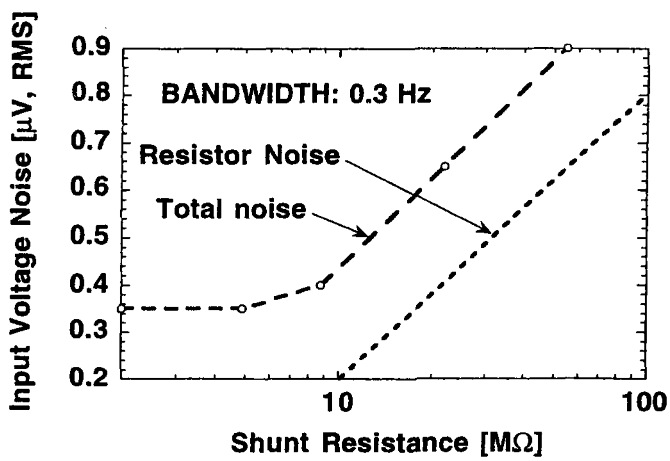

Figure 5. Shunt resistance dependent input total voltage noise (measured) and resistor noise (calculated) of the InGaAs radiometer.

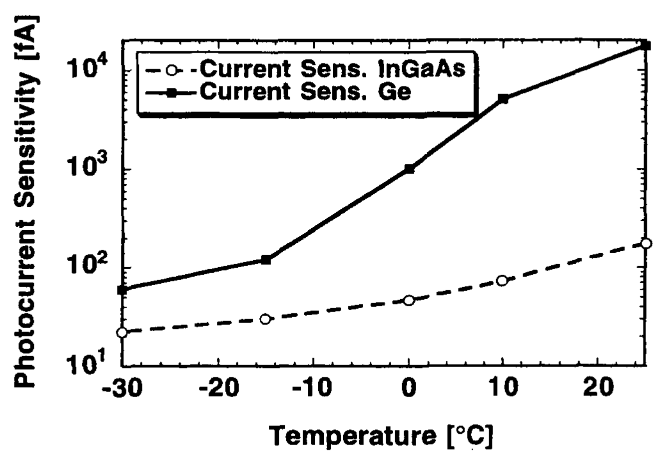

Figure 6. Temperature dependent photocurrent sensitivities of the Ge and InGaAs radiometers

During an 8 hour stability measurement, when the temperature was regulated at -30 °C and the signal gain was 10^9 V/A, the Ge radiometer showed a DC dark-current change of 0.5 pA. The DC dark-current change of the InGaAs radiometer under similar conditions was 0.2 pA during 16 hours.

3. DYNAMIC (AC) CHARACTERISTICS OF THE NIR RADIOMETERS

It is important to know the current-, voltage-, and loop-gain characteristics versus frequency for any photodiode I-V converter. The current gain is important, because the signal is the photocurrent. The high frequency roll-off of the current gain (response) curve is determined by the time constant given by the feedback resistor and capacitor of the I-V converter[5]. The voltage amplification of the I-V converter is equal to the closed loop voltage gain. The voltage gain versus frequency characteristics are important for all current (signal) gain ranges because these curves show whether the meter has any noise boosting effect (increased gain for a certain frequency interval) within the measurement bandwidth.

Figure 7 shows the calculated voltage gain curves of the two NIR radiometers at a current-to-voltage gain of 10^9 V/A. The only capacitor connected in parallel to the R=1 GΩ feedback resistor is the C=2 pF (estimated) stray capacitance. The voltage gain roll-on for the Ge radiometer starts at 0.23 Hz. This roll-on frequency is determined by the time constant calculated from the product of two factors. One factor is the resultant resistance of the parallel connected feedback and photodiode shunt resistances. The other factor is the sum of the photodiode and feedback capacitances[6]. For this time constant, the dominating resistance is the shunt resistance, R_S, and the dominating capacitance is the junction capacitance, C_j. The junction capacitance is 36 nF for the Ge photodiode and 0.5 nF for the InGaAs photodiode. The shunt resistance of the Ge photodiode is 20 MΩ and that of the InGaAs photodiode is 55 MΩ at -30 °C. Accordingly, the roll-on frequency of the InGaAs radiometer is about 40 times higher than that of the Ge radiometer. The noise boosting effect starts at the roll-on frequency. The noise boosting can be eliminated if the roll-off time constant (given by the feedback impedance) is tuned to the roll-on time constant. This is called full frequency compensation. Frequently, full compensation cannot be achieved at high signal gains because the roll-off of the signal gain curves can be too low. In this situation partial compensation will decrease the noise boosting effect while keeping the signal gain roll-off at high enough frequencies.

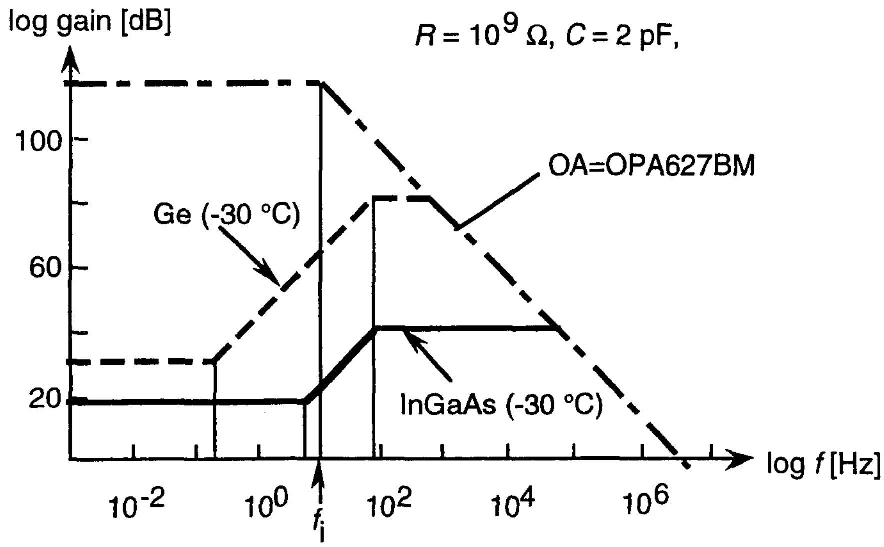

Figure 7

Frequency dependent voltage gain characteristics of the Ge and InGaAs radiometers

The DC characteristics were measured at a bandwidth of 0.3 Hz for both radiometers. Consequently, all measurements were made outside of those frequency intervals where the noise boosting is significant. The voltage gain curves also show that the low frequency (DC) amplification of the input voltage noise is about three times larger with Ge as compared to InGaAs. Similarly, the noise boosting effect at higher frequencies is roughly two decades higher with Ge as compared to InGaAs.

The shape of the loop gain curve (of the open analog control loop) shows whether the loop gain, G, is high enough at the signal frequency to achieve accurate and stable current-to-voltage conversion[7]. This requirement is important for both chopped (or modulated) and low frequency (DC) signal measurements. The OPA627BM operational amplifier selected for chopped radiation measurement has a larger DC open loop gain and a higher open loop gain roll-off point, f_i, than the OPA111 used at DC signal measurements. f_i is determined by the dominating integration time-constant of the operational amplifier. The shape of the loop gain curve indicates whether the phase shifts are small enough for frequencies within the loop bandwidth. Phase shifts for noise frequencies, equal to 180° or larger, can produce oscillations in the analog control loop of the I-V converter.

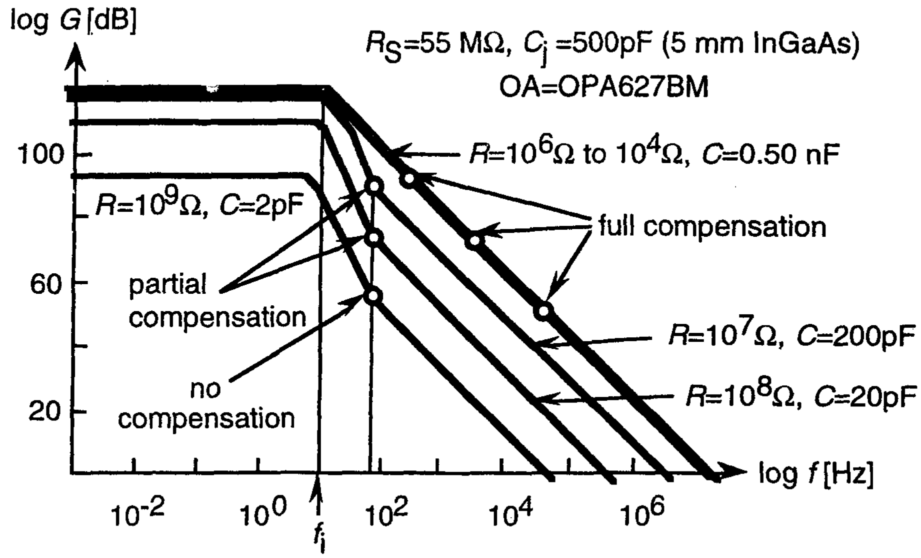

Figure 8. Frequency dependent loop gain characteristics of the InGaAs radiometer for different feedback resistors

Figure 8 shows the calculated loop gain versus frequency curves of the InGaAs radiometer for different feedback resistors. The roll-off points of the signal gain curves are shown with circles as they are matched to the loop gain curves. As a result of partial and full compensations, the roll-off points of the signal gain curves are at 80 Hz or higher. At a chopping frequency of about 10 Hz the loop gains are all larger than 10^4. If the chopping frequency is increased to 80 Hz, the loop gains are still equal or larger than 10^3. Because of the large loop gains at frequencies below 80 Hz, the relative uncertainty (coverage factor k=1) contribution from the loop gains will not be higher than 0.1 % in the photocurrent measurements.

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